Production of a Roll-off Equipped Harwarder for Forest Biomass Utilization

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Abstract

Detailed time-and-motion studies were conducted on a harvesting system that included roll-off bins and bunks used in conjunction with a Timbco harwarder at two study sites in western Montana. Data from these studies were used in multiple regression analysis to develop production equations for total cycle time for each of the seven processes involved in harvesting roundwood products and woody biomass. Independent variables used to create these production equations included distance traveled, piece size, number of pieces, and a site term. Comparisons were made between developed equations from this study and other published equations. Using standardized variables, production rates (tons/hour) of the observed processes were developed. Forest managers can apply these equations to determine the cycle time for a process and, when paired with tons per cycle, the production rate of the roll-off and hook-lift system can be determined and compared to other roundwood and biomass harvesting and treatment options.

Keywords: Harwarder, roll-off, woody biomass, time-and-motion, total cycle time equation.

Introduction

In the western United States, forest slash has traditionally been hand or machine piled and then burned in the woods. Another option for slash management is to collect the slash and utilize it for production of biofuel based energy. With potentially high fuel loadings, air quality restrictions, short windows of appropriate weather, and risk of fire escape in the wildland-urban interface, biomass utilization is an attractive alternative to open-air burning (Rummer *et al.* 2005). Logging residues have long been acknowledged as a potential source of energy, but the high costs of collecting and transporting these materials have restricted their use (Watson *et al.* 1986, Rummer *et al.* 2004, Nicholls *et al.* 2008). To be economically feasible, woody biomass harvest operations need to be cost efficient (Rummer *et al.* 2005, Western Governors' Association 2006).

Chip vans have historically been the most efficient way to transport ground material (hog fuel) from the grinding site at landings to a processing facility. Transporting ground biomass with chip vans is only appropriate for landings adjacent to highways or other high standard roads. Forest roads, with typically inadequate vertical and horizontal alignment, are generally not suitable for chip vans (Hanson 2007, Rawlings *et al.* 2004). As a result, forest managers are often forced to pile and burn logging residue.

Past attempts of harvesting and transporting traditionally non-merchantable material have involved ground-based whole-tree systems (Miller *et. al.* 1987, Mitchell *et. al.* 2007, Watson *et. al.* 1986), cut-to-length systems (Hanson 2007), and bundling systems (Cuchet *et. al.* 2004, Rummer *et. al.* 2004). Generally, ground-based whole-tree systems are the most cost-efficient means of moving forest residues to the landing (Miller *et. al.* 1987, Mitchell *et. al.* 2007, Watson *et. al.* 1986).

The goal of using roll-off bins and bunks is to eliminate multiple handling of woody biomass material. "Roll-off" refers to modular containers that are "rolled" onto, and off of, the haul truck or forwarder by use of a hydraulic hook-lift (Han 2008). The roll-off system allows the extraction of material that would typically go unused because of access restrictions. The roll-off and hook-lift system that was the focus of this study consists of two modified machines: (1) a modified forwarder with a quick attach system so that an accumulating hotsaw, a dangle-head processor, and a grapple were quickly

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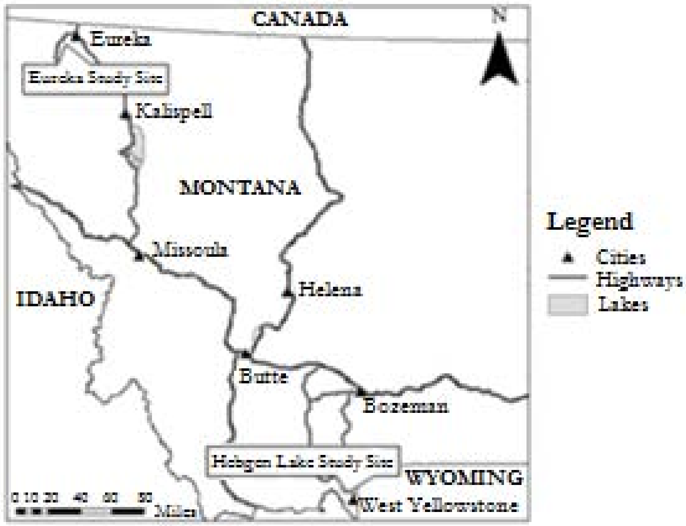

Figure 1. Map of study sites.

interchangeable (referred to as a "harwarder") and (2) a haul truck with a pup trailer. Both machines were equipped with hydraulic hook-lifts that were used to load and unload bins or bunks, which was hypothesized to lead to considerable time savings with material transfer (Atkins et al. 2007).

The purpose of this study was to develop predictive total cycle time equations to characterize the roll-off and hook-lift system in order to determine the production levels (tons/hour) for system processes. A time-and-motion study was conducted to identify significant independent variables and develop total cycle time equations and production rates (tons/hour). This information will be useful for forest managers facing unfavorable burning conditions and developing markets for woody biomass from logging and thinning restoration treatment operations.

Methods

Study Sites

Harvest activities and biomass handling techniques were observed at sites in the northern Rocky Mountains near Eureka and West Yellowstone, Montana (Figure 1). The two study sites were selected from fire hazard reduction projects planned for implementation by the U.S. Forest Service. The two sites were topographically similar: the Hebgen Lake site was level and the Eureka site was relatively flat with infrequent short, steep pitches of terrain.

The Eureka site (6.2 ha (15.3 acres), Figure 2) consisted of a mixed-conifer stand that included ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*). Pre-harvest basal area was 35 m^2/ha (154 ft^2/acre). The harvest prescription for the Eureka site called for removing trees less than 30.5 cm (12 inches) DBH (diameter at breast height) to increase residual tree spacing to enhance growth. The Hebgen Lake study site (31 ha (76 acres), Figure 3) was a pure stand of lodgepole pine (*Pinus contorta*). Pre-harvest basal area was 13 m^2/ha (56 ft^2/acre). The harvest prescription for the Hebgen Lake site was a general thinning aimed to reduce stand density and promote growth of dominant and co-dominant residual trees. Roads ran throughout the units. Several private cabins were located adjacent to the study site on leased Forest Service land.

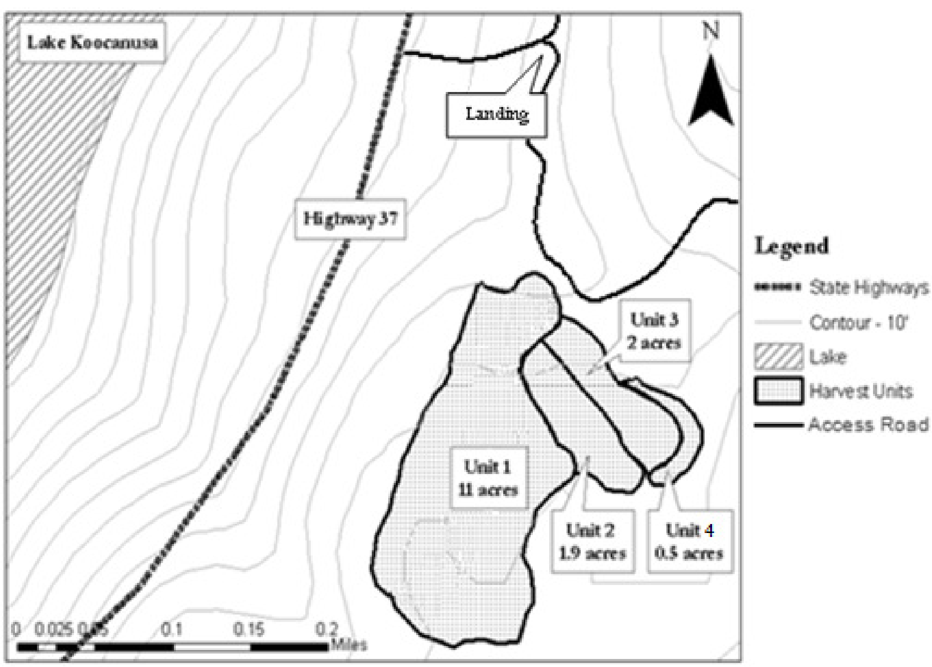

Figure 2. Eureka study site.

Harvest System

The harvest system studied included a modified 820C Timbco harwarder and 1989 Peterbilt Class 8 truck, each equipped with a Stellar 23587 kg (52,000 lb)-capacity hydraulic hook-lift. Roll-off bins measuring 7.3 m (24 feet) long, 2.4 m (8 feet) tall, and 2.4 m (8 feet) wide and roll-off bunks measuring 7.3 (24 feet) long, 2.4 (8 feet) tall, and 3 m (10 feet) wide were used with the harwarder and truck. Bins were fabricated with a taper, which allowed up to three empty bins and bunks to be stacked and moved at once.

The Peterbilt truck with a hook-lift was used for on-road transportation of slash and roundwood products. The truck was capable of delivering legal full loads of 27 tonnes (30 U.S. short tons, hereafter "tons") when using a pup trailer, which was also modified to carry roll-off bins and bunks. Since the trailer was not self-loading it relied

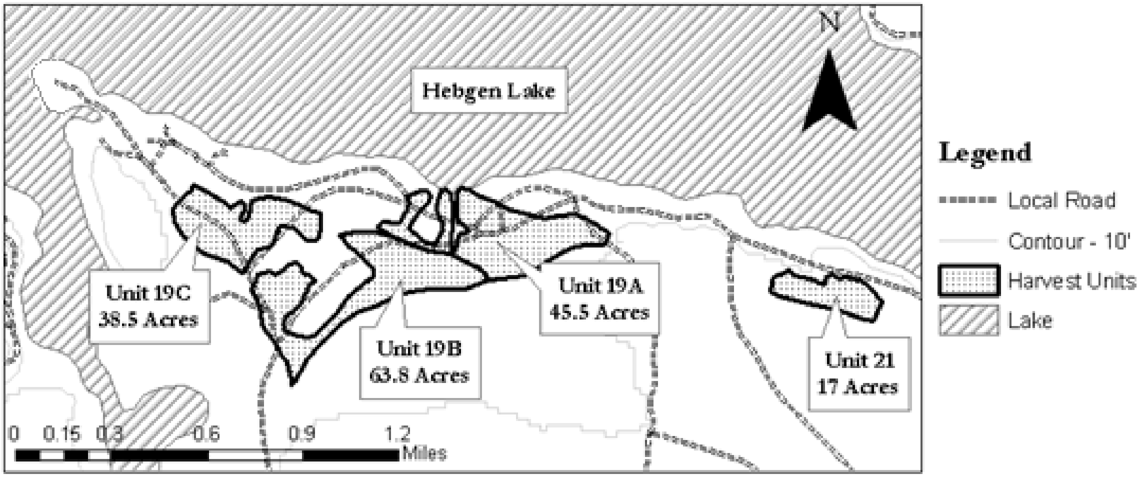

Figure 3. Hebgen Lake study site sites.

on the truck to load bins and bunks.

For portions of the study, hand felling was used to cut trees less than 11.4 cm (4.5 inches) DBH. Hand felling was performed by a worker using a professional-grade chainsaw.

A John Deere 648G rubber-tired grapple skidder was used in one unit at Eureka. When the skidder was used, the harwarder cut and bunched whole-trees and then served as a stationary delimber at the landing in order to model a ground-based whole-tree harvesting system.

At Eureka four units were treated totaling 6.2 ha (15.3 acres) (Table 1). Units were small due to modifications made to the harvesting system as researchers and the operator tried new processes to determine what was most efficient. Harvesting activities occurred during January and February of 2008 with 0.2 to 0.3 m (0.5 to 1 foot) of snow on the ground. Observations from Eureka were used to direct efforts at the Hebgen Lake study site. Hand felling of trees less than 11.4 cm (4.5 inches) DBH was used in all of the Hebgen Lake Units (Table 1). In Unit 19A(b) a slash mat was created to minimize soil disturbance and test if creating a slash mat had any significant impact on the total cycle time. Harvesting activities took place in June and July of 2008 under dry conditions.

Diversity in stand conditions, cutting season, and system combinations was desirable given the planned multivariate regression approach to the analysis of independent variable relationships for predicting total cycle times.

Data Collection and Analysis

Each component of the harvest system underwent a detailed time-and-motion study using a stopwatch (Table 2). Cycles were identified when the process started to repeat itself. Independent variables were selected after observing each process and breaking cycles down into logical components. Such variables included travel distance or tree DBH, for example, that were measured using ocular estimates by one researcher in the field with periodic calibration using a diameter tape, hip chain, and maps. Non-productive delays were recorded and used to calculate utilization rates by process. A utilization rate is the productive machine time (total observed time minus non-productive delay time) divided by the scheduled machine time (all of the observed activity time, including all delays). Non-productive delays included activities that were not necessary for production such as repairs and worker personal time. Productive delays were activities that occurred on a daily basis and were necessary for production, such as warming up and fueling machines. These sample observations were used to develop total cycle time equations for the observed processes.

Some processes did not have defined cycles or a regression equation was not developed. These processes included hand felling, loading and transporting roundwood, transporting slash, and slash grinding. The lack of a defined cycle was due to the inability to identify independent variables and logical time elements or the inability to record time elements within a process. For example, hand felling was a process with logical components and independent variables. However, it was impractical to record this information since this cycle was often less than one second in duration when cutting in thickets of small trees.

Green tonne per tree was calculated using equations from Jenkins *et al.* (2004) on a species and product-type basis. Product types were defined by DBH ranges (Table 3). By assuming the number of trees per cycle, product mix, and species composition, the tons per cycle could be calculated. Based on measurements of moisture content of slash during the Hebgen Lake study, green moisture content was assumed to be 44% for both study sites. Tons per cycle for forwarding was assumed to be a constant 13.6 tonnes (15 tons) per turn for forwarding roundwood and 5.0 tonnes (5.5 tons) per turn for forwarding slash. The roundwood forwarding value was provided by the forest contractor and the slash forwarding value was determined by using a scale at the concentration yard.

Using SPSS version 17 (SPSS 2008) backwards stepwise linear regression was used to develop total cycle time models for each process of interest. A total cycle time was the amount of time (delay free) to complete one cycle of a given

Table 1. System description and acreage of each study unit at the Eureka and Hebgen Lake sites.

Site	Unit	Area	System
Eureka	1	4.4 ha (11.0 ac)	The hotsaw felled all trees. The dangle-head processor delimbed and topped roundwood in the woods. All material was forwarded on bunks to the landing. Roundwood was hauled to the mill via the hook-lift haul truck and slash was left to dry at the landing.
	2	0.8 ha (1.9 ac)	The hotsaw felled all trees. Roundwood was skidded to the landing. Material <11.4 cm (4.5 in) DBH was forwarded to the landing using the harwarder and roll-off bunks. Roundwood was processed at the landing with the dangle-head processor. Slash was piled by the skidder at the landing.
	3	0.8 ha (2.0 ac)	Trees <11.4 cm DBH were hand felled. Trees ≥11.4 cm DBH were felled and processed by the dangle-head processor. Roundwood was forwarded on bunks. Slash and trees <11.4 cm DBH were mechanically piled in the woods.
	4	0.2 ha (0.5 ac)	The dangle-head processor felled and processed all trees. Roundwood was forwarded to the landing. Slash and trees <11.4 cm DBH were mechanically piled in the woods.
Hebgen Lake	19A(a) 19C(a) 21	12.3 ha (30.3 ac) 3.9 ha (9.6 ac) 6.9 ha (16.96 ac)	Trees <11.4 cm DBH were hand felled. Trees ≥11.4 cm DBH were felled and processed by the dangle-head processor. Roundwood was forwarded on bunks and slash was forwarded in bins. The hook-lift truck transported slash bins to the concentration yard. Roundwood was transported to processing facilities in bunks by the hook-lift truck.
	19A(b)	4.1 ha (10.1 ac)	Trees <11.4 cm DBH were hand felled. Trees ≥11.4 cm DBH were felled and processed by the dangle-head processor with slash placed in trails. Roundwood was forwarded on bunks and slash was forwarded in bins. The hook-lift truck transported bins of slash to the concentration yard. Roundwood was transported to processing facilities in bunks by the hook-lift truck.
	19C(b)	3.9 ha (9.6 ac)	Trees <11.4 cm DBH were hand felled. Trees ≥11.4 cm DBH were felled and processed by the dangle-head processor. Roundwood was forwarded on bunks. Roundwood was transported to processing facilities in bunks by the hook-lift truck. Slash was piled in the unit by the harwarder.
	19C(c)	7.8 ha (19.3 ac)	All material was manually cut and piled for burning.

process. Observed variables were considered significant, or retained in a model, if they had a p-value ≤ 0.05.

Production rates in tonnes per hour were calculated using total cycle time equations for each process. Using tons per cycle with standardized variables for the productive total cycle time equations, production rates were calculated by dividing tonnes per cycle by cycle time. Production rates were calculated using known cycle tonnages as provided from the forest contractor or using tonnages calculated per Table 3. All production rates were free of non-productive delays. Using the delta method (Davison 2003), 95% confidence intervals were included with the production rates.

Results

Production Equations

Six independent variables were determined to be significant throughout the observed processes: distance between stops and in total, stem diameter, number of pieces per tree and per cycle, and a site variable. Observed processes were part of four groupings: (1) felling, (2) processing, (3) forwarding, and (4) skidding. Within these four groupings, seven models were developed for observed processes.

1. Hotsaw

The hotsaw was only used in Unit 1 at Eureka. The hot-

Table 2. Number of total cycles and time included in detailed time-and-motion study.

Site	Process	(a) Total Cycles Observed	(b) Total Time Observed (min)	(c) Non-Productive Delay Time Observed (min)	(d=b-c) Productive Time Observed (min)	(e=d/b) Utilization Rate (%)
Eureka	Hotsaw	416	739.8	85.2	654.6	88%
	Hand Felling	N/A	218.0	45.3	172.7	79%
	Processing	451	485.4	119.7	365.7	75%
	Dangle-Head Processor Felling and Processing	841	525.3	76.8	448.5	85%
	Forwarding Roundwood	4	139.6	14.8	124.8	89%
	Forwarding Slash	7	190.9	5.5	185.4	97%
	Whole-tree Skidding with Rubber Tired Skidder	5	56.7	0.0	56.7	100%
	Mechanical Brush Piling	12	103.0	0.0	103.0	100%
	Loading and Transporting Roundwood	N/A	356.2	154.3	201.9	57%
Eureka Totals			2814.9	501.6	2313.3	
Hebgen Lake	Forwarding Roundwood	4	271.1	108.8	162.3	60%
	Forwarding Slash	8	531.8	170.3	361.5	68%
	Hand Felling	N/A	83.6	2.4	81.2	97%
	Dangle-Head Processor Felling and Processing	805	852.7	340.2	512.5	60%
	Mechanical Brush Piling	21	243.0	45.0	198.0	81%
	Transporting Slash	N/A	94.5	57.7	36.8	39%
	Grinding	N/A	503.8	210.2	293.6	58%
Hebgen Lake Totals			2580.5	934.6	1645.9	
Total For Both Study Sites			5395.4	1436.2	3959.2	

saw cycle consisted of travel time (14.7% of total cycle time), felling time (85.1%), and productive delays (0.2%). All of the recorded variables were significant. (Adjusted R^2 = 0.399, SEE = 1.7, N = 416):

$$T_{HS} = 0.671 + 0.021(D_s) + 0.253(N_t))$$

where:

T_{HS} = Total cycle time for hotsaw (minutes)

D_s = Distance traveled between stops within the unit (feet)

N_t = Number of trees per cycle

2. Felling and Processing in Woods with Dangle-Head Processor

Felling and processing with the dangle-head consisted of travel time (16.4% of total cycle time), reaching for the tree (27.6%), felling and processing (55.5%), and productive delays (0.5%). Sawyer pre-treatment and slash mat creation were found to be not significant. (Adjusted R^2 = 0.548, SEE = 0.21, N = 1646):

$$T_{DP} = -0.118 + 0.013(D_s) + 0.089(DBH) + 0.061(N_r))$$

where:

T_{DP} = Total cycle time for felling and processing in woods with dangled-head processor (minutes)

D_s = Distance traveled between stops within the unit (feet)

DBH = DBH of cut tree (inches)

Table 3. Green tonnes per tree by species and product type, from Jenkins et al. (2004)

Product Type	DBH Range		ponderosa pine	Douglas-fir	western larch	lodgepole pine
	cm	inches				
Slash	≤ 11.4	≤ 4.5	0.017	0.024	0.020	0.017
Pulpwood/Poles	11.5-17.8	4.5 – 7	0.077	0.106	0.080	0.077
Sawlog	17.9-33.0	7 – 13	0.399	0.556	0.368	0.399

N_r = Number of roundwood pieces recovered per tree

3. Dangle-Head Processor – Processing from Hotsaw Piles

Processing from log piles in the woods consisted of travel time (8.2% of the total cycle time), selecting a tree from the pile (45.0%), and processing (46.8%). The number of trees processed at once and the number of roundwood pieces recovered from a tree was found to be not significantly different than one and therefore was not significant in predicting total cycle time. (Adjusted R^2 = 0.405, SEE = 0.43, N = 333):

$$T_{DPH} = 0.286 + 0.007(D_s) + 0.043(DBH)$$

where:

T_{DPH} = Total cycle time for dangle-head processor processing from hotsaw piles (minutes)

D_s = Distance traveled between stops within the unit (feet)

DBH = DBH of cut tree (inches)

4. Processing at Landing with Dangle Head Processor

Processing at the landing with the dangle-head processor consisted of selecting a tree from the pile (30.7% of total cycle time) and processing the tree(s) into logs (69.3%). The number of roundwood pieces recovered from a tree was found to be not significantly different than one and therefore was not significant in predicting total cycle time. (Adjusted R^2 = 0.578, SEE = 0.12, N = 117):

$$T_{DPL} = -0.383 + 0.102(DBH) + 0.043(N_t)$$

where:

T_{DPL} = Total cycle time for processing trees at the landing with the dangle-head processor (minutes)

DBH = DBH of cut tree (inches)

N_t = Number of trees per cycle

5. Forwarding Slash (with or without Slash Mat)

Slash forwarding when using a bunk consisted of travel time (41.5% of total cycle time), slash loading (55.6%), and slash unloading (2.9%). When using a bin, the slash was forwarded to the landing where the full bin was off loaded and an empty bin was picked up. Slash forwarding when using a bin consisted of travel time (20.6%), slash loading (74.5%), compacting the slash within the bin (1.5%), unloading the bin (1.3%), and loading an empty bin (2.1%).

When both Hebgen Lake and Eureka data were included in an analysis, a model with no significant variables resulted, rendering it non-useable. The reason for the differences between the two sites could not be determined statistically. Since slash mat and hand felling usage changed between sites, the difference could in part be attributed to the impact of either of these variables. Similarly, using bins versus bunks for forwarding slash was unable to be tested for significance since only bins were used at Hebgen Lake and only bunks were used at Eureka. Furthermore, it was not possible to test for the significance of a slash mat when forwarding slash at Hebgen Lake because data were only collected for this condition. Likewise, site was not tested for significance because of the inconsistencies between the two data sets. Because of these statistical issues, only data from Eureka were used. Hand felling was determined to be not statistically significant at Eureka. All of the recorded variables were found to be significant. (Adjusted R^2 = 0.716, SEE = 4.07, N = 7):

$$T_{FS} = 11.079 + 0.012(D_t)$$

where:

T_{FS} = Total cycle time for forwarding slash (minutes)

D_t = Total distance traveled within the unit (feet)

6. Forwarding Roundwood Material

Forwarding roundwood material consisted of travel time (38.2% of total cycle time), loading material (42.4%), and unloading material (19.4%). At both study sites, roundwood pieces were unloaded individually using the grapple, not unloaded in bulk by offloading the full bunk. Roundwood product type was determined to not be significant in predicting total cycle time within Eureka. However, roundwood product type did change between study sites; sawlogs and pulpwood were removed at Eureka and poles at Hebgen Lake. A site term was statistically significant, which may account for differences such as stand conditions, harvest conditions, weather conditions, and operator skill level. The number of roundwood pieces handled was determined to be not significant. (Adjusted R^2 = 0.992, SEE = 5.48, N = 8):

$$T_{FR} = 0.018(D_t) + 23.19(X)$$

where:

T_{FR} = Total cycle time for forwarding roundwood material (minutes)

D_t = Total distance traveled within the unit (feet)

X = Site term (0 if Eureka; 1 if Hebgen Lake)

7. Rubber-Tired Grapple Skidder

The skidding process consisted of travel time (70.3% of total cycle time), loading time (7.5%), and unloading time (22.2%). All of the recorded variables were found to be significant. The number of stems per turn was not recorded in the field but photographs indicate an approximate average of 15 roundwood pieces per turn with the majority of stems being pulpwood sized. (Adjusted R^2 = 0.966, SEE = 1.87, N = 5):

$$T_{GS} = 0.003(D_t)$$

Table 4. Production rate by process with 95% confidence (tonnes/productive machine hour (PMH)).

Process	Tonnes/PMH	Tons/PMH
Hotsaw	12.2 ± 0.9	13.5 ± 1.0
Felling and processing with dangle-head processor	8.4 ± 0.2	9.3 ± 0.2
Processing from hotsaw piles in the woods	10.7 ± 1.7	11.8 ± 1.9
Processing at the landing	29.8 ± 1.5	32.9 ± 1.6
Forwarding slash with a roll-off bin	10.3± 3.2	11.3± 3.5
Forwarding roundwood	30.2 ± 6.3	33.3 ± 6.9
Skidding roundwood with grapple skidder	54.1 ± 14.8	59.6 ± 16.3

where:

T_{GS} = Total cycle time for rubber-tired grapple skidder (minutes)

D_t = Total distance traveled within the unit (feet)

Production Rates

Based on the developed models, potential production rates (tonnes/productive machine hour (PMH)) were estimated for observed processes. To calculate these rates, input values were assigned for the total cycle time equation variables assuming harvest conditions similar to the Eureka site, a total cycle travel distance of 457 m (1500 ft), 15.25 cm (6 inches) DBH with one roundwood piece recovered per tree, and all processes working with one stem per cycle except the hotsaw, where four stems per cycle were assumed. Additionally, an assumed product mix of 5% sawlogs, 51% pulpwood, 24% slash from tops and limbs, and 20% stems smaller than 11.5 cm (4.5 inches) by weight and a species composition of 10% ponderosa pine, 75% Douglas-fir, and 15% western larch was used. For example, to estimate the total cycle time of forwarding slash, a travel distance of 457 m (1500 ft) would be entered into the forwarding slash equation resulting in a cycle time of 21.9 minutes. Tonnes per cycle for forwarding slash was known to be 5.0 tonnes (5.5 tons) so the estimated production rate would be 10.3 tonnes/PMH (11.3 tons/PMH). Average skidding distance was assumed to be one half of the forwarding distance. Travel distance between stops was calculated as a function of stand density.

Production rates for all processes are displayed in Table 4. Felling with the hotsaw (12.2 tonnes/PMH) was slightly more productive than felling and processing with the harvester's dangle-head processor (8.4 tonnes/PMH). Stand-alone processing options are estimated to produce 10.7 tonnes/PMH for processing out of piles in the woods or 29.8 tonnes/PMH to process whole-trees using the same processing head at the landing. Whole-tree skidding with a rubber-tired grapple skidder (54.1 tonnes/PMH) was nearly twice as productive as forwarding roundwood in bunks (30.2 tonnes/PMH) and five times as productive as forwarding slash in bins (10.3 tonnes/PMH).

Discussion

Regression analysis indicated that site was significant for roundwood forwarding. Hebgen Lake total cycle times were longer with shorter forwarding distances as compared to Eureka. The specific reason for the increased cycle time was impossible to determine statistically because of the numerous differences between the two sites such as operating over snow, stand structure and composition, and roundwood product type. After referring to notes and contractor experience, the most logical cause for the increase was due to operating in a developed area near cabins and power lines at the Hebgen Lake study site. These conditions required additional attention and time when loading roundwood pieces into the bunk to avoid hitting cabins and power lines. Similarly, extra care was needed when traveling.

Several comparisons were made between developed total cycle time equations and published total cycle time equations of similar processes. Figure 4 displays the relationship between total cycle time and travel distance for forwarding roundwood developed in this study along with equations from Dodson Coulter (1999), Kellogg *et al.* (2004), McNeel *et al.* (1994), and Wang *et al.* (2005). Forwarder load size (number of pieces) was similar across all studies. Figure 5 shows that when the number of pieces per load was set to 200, the equation developed in this study had a similar slope to many of the other published equations; however, the total cycle time values of this study's equation more closely matched that of McNeel *et al.* (1994). The differences in total cycle times could be caused by several factors including terrain type (steep or level), residual stand conditions (densely stocked, which would hinder maneuverability), weather conditions (snow or ice that may limit travel), and finally travel speed (affected by either horsepower or conditions previously listed).

Using the dangle-head processor to fell and process trees was compared to published total cycle time equations for harvesters. Figure 5 displays the relationship between total cycle time and DBH for felling and processing with the dangle-head developed in this study and compares it to equations from Kellogg *et al.* (2004), Rummer *et al.* (2002), and Dodson Coulter (1999) assuming harvesting one tree at a time and a travel distance between trees of 6.1 m (20 feet). As DBH in-

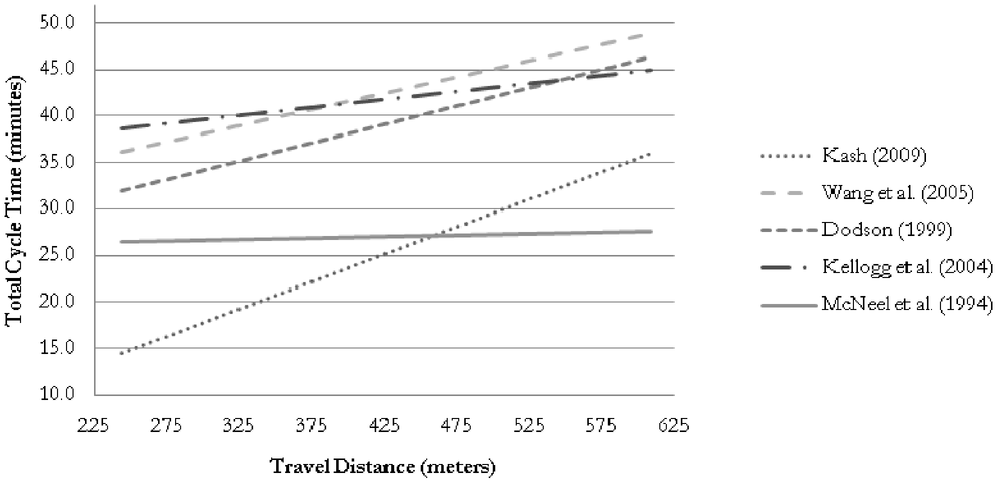

Figure 4. Forwarding roundwood comparisons.

creases the estimated production rate (tonnes/hour) will diverge at a fluctuating rate (Figure 6). The equation from Rummer *et al.* (2002) would estimate the least productive cutting and processing time while the equation from Kellogg *et al.* (2004) would estimate the most productive system for trees between 12.7 and 43 cm (5 and 17 inches) DBH. The large spike in Figure 6 at a DBH value of 17.8 cm (7 inches) was due to the difference in tonnes per cycle when changing from pulpwood/poles to sawlog sized trees. The reason that Rummer *et al.* (2002) had a lower production rate may be due to using a smaller harvester that was only capable of handling 48.2 cm (19 inch) DBH trees. This smaller capacity machine could have longer cycle times while handling larger trees when compared to a larger harvesting head that would function more easily. The difference with Kellogg *et al.* (2002) is difficult to assess. The reason for the lower total cycle times could be due to operator inexperience or harvest conditions.

Conclusion

Total cycle time equations developed for timber harvesting and biomass utilization using hook-lift technology were developed for the intermountain west with interesting findings. Site location was significant for forwarder total cycle times, though a specific cause was not determined. There was also a significant difference between processing at the landing versus processing in the woods. When processing at the landing, total cycle time increased faster than processing in the woods, as DBH increased but was still the preferred method for the studied DBH range. It is believed that the cause for this difference is due to the harwarder having to maneuver around accumulating slash at the landing. Finally, when comparing total cycle times developed in this study to previous publications, results fall within reasonable limits of others' findings. Forest managers can apply independent variables to the equations developed in this study to estimate the production rate of various machines and determine if those production levels are appropriate for their forest conditions, harvest constraints, and logistical demands.

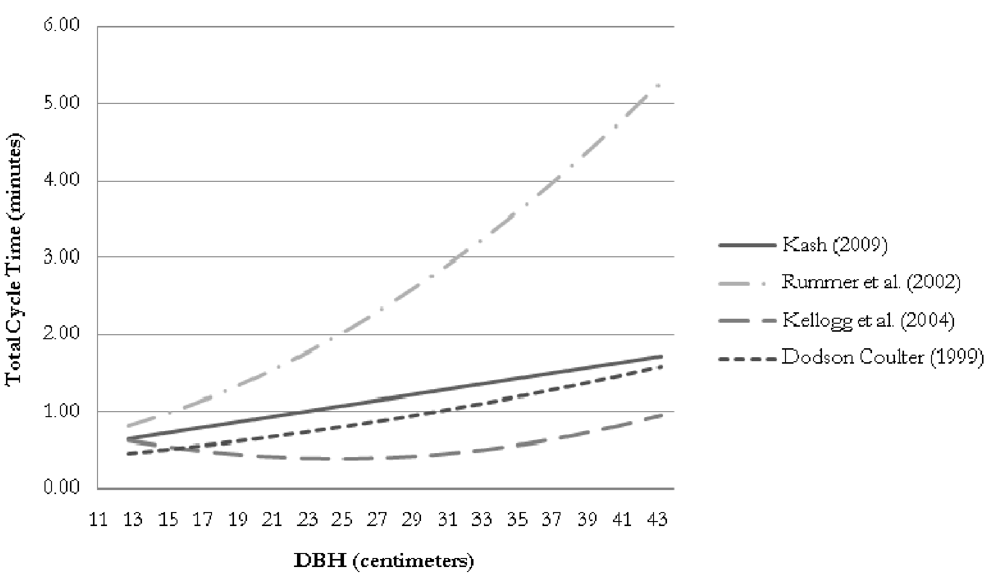

Figure 5. Dangle-head processor felling and processing total cycle time comparisons.

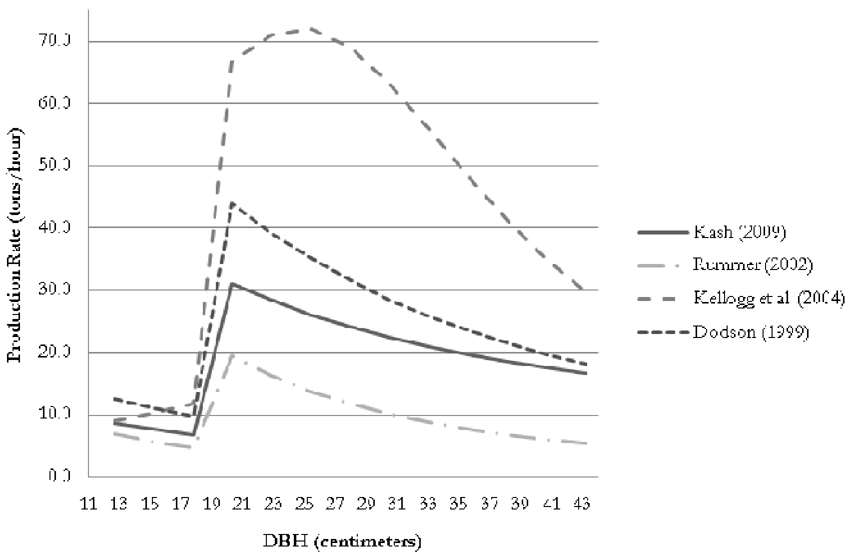

Figure 6. Dangle-head processor felling and processing production rate comparisons.

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